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Pulsar Nulling and Mode Changing

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ABSTRACT

With its relatively long observation time per pointing, the Parkes multibeam survey was effective in detecting nulling pulsars. We have made 2-hour observations of 23 pulsars which showed evidence for pulse nulling or mode changing in the survey data. Because of the low flux density of these pulsars, in most cases averaging times of between 10 s and 60 s were necessary and so this analysis is insensitive to very short nulls. Seven of the pulsars had null fractions of more than 40% with the largest having a lower limit of 95%. Mode changes were observed in six pulsars with clear relationships between nulling and mode changing in some cases. Combined with earlier results, the data suggest that large null fractions are more related to large characteristic age than to long pulse period. The observations suggest that nulling and mode changing are different manifestations of the same phenomenon.

Key words: pulsars: general — radiation mechanisms: non-thermal

1 INTRODUCTION

Observed pulsar radio flux densities vary on many timescales. Some of these variations result from scintillation due to scattering of ray paths by fluctuations in the interstellar electron density (Rickett 1990). Diffractive scintillation occurs on relatively short timescales, typically minutes to hours, but can usually be avoided by averaging over wide bandwidths. At least when averaged over timescales of many minutes, the intrinsic luminosity of most pulsars is apparently very stable (Kaspi & Stinebring 1992). However, on shorter timescales, a wide variety of fluctuation phenomena are observed. In all pulsars, the pulse energy fluctuates from pulse to pulse, with modulation indices often greater than unity (Taylor et al. 1975; Weltevrede et al. 2006). In some pulsars, these modulations are quasi-periodic, often only affecting part of the pulse profile (e.g., Backer 1973). These fluctuations appear to be closely related to the drifting subpulses seen in some pulsars (e.g., Taylor et al. 1975).

All of these modulations are basically continuous, that is, in a given pulsar they are present most or all of the time. Pulsars also exhibit a different class of intensity modulation which is characterised by discontinuous transitions between otherwise stable modes. Pulse nulling is a phenomenon in which the pulse energy suddenly drops to zero or near zero and then just as suddenly returns to its normal state (Backer 1970b). Nulling is relatively common in pulsars. Based on data for 72 well-observed pulsars, Biggs (1992) found evidence for nulling in 43. Nulls vary widely in duration, from just one or two pulses to many hours or even days, and in "null fraction" (NF), the fraction of time that the pulsar is in a null state, which can range from zero (for the Vela pulsar) to more than 50%. Ritchings (1976) found that the NF was correlated with pulsar age, with older pulsars more likely to null, but Biggs (1992) found a better correlation with pulse period. Recently Kramer et al. (2006) showed that in PSR B1931+24, which has long-duration quasi-periodic nulls with a cycle time of about 40 days, the slow-down rate is reduced by about one third when the pulsar is in a null state, demonstrating that the magnetospheric currents responsible for the pulse emission also contribute to the pulsar braking.

Mode changing is another kind of discontinuous change where the mean pulse profile abruptly changes between two (or sometimes more) quasi-stable states. It was first observed in PSR B1237+25, a five-component pulsar in which pulse power occasionally switches from the trailing two components to the central component (Backer 1970a). Subsequent observations have revealed mode changing in a dozen or so pulsars, most of which have multi-component profiles. Many of these pulsars also exhibit drifting subpulses and nulling (van Leeuwen et al. 2002; Janssen & van Leeuwen 2004; Redman et al. 2005). Drifting, quasi-periodic modulation, microstructure and polarisation properties are all affected by mode changing (Taylor et al. 1975; Bartel et al. 1982; Rankin 1986; Gil et al. 1994) showing that it represents a fundamental change in the emission process. Both nulling and mode changing are broad-band and they may

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be different manifestations of the same basic phenomenon. Observations of pulse nulling are often limited by signal-to-noise ratio and in practice a null is only an absence of detectable emission, with the best limits $\lesssim$ 1% of the mean intensity (Biggs 1992; Kramer et al. 2006). For PSR B0826−34, averaging of data within apparent nulls has revealed weak emission within the "null" intervals at a level of $\sim$ 2% of the mean "on" flux density (Esamdin et al. 2005). Interestingly, the pulse profile is different to that observed when the pulse is strong, showing that the effect is really a mode change.

In this paper we present observations of 23 mostly southern pulsars, made using the Parkes 64-m radio telescope at 1500 MHz. These pulsars, many of which were discovered in the Parkes multibeam pulsar survey (Manchester et al. 2001), have no previously published pulse fluctuation data. In §2 we describe the observations and our results and in §3 we discuss the implications of the results and give our conclusions.

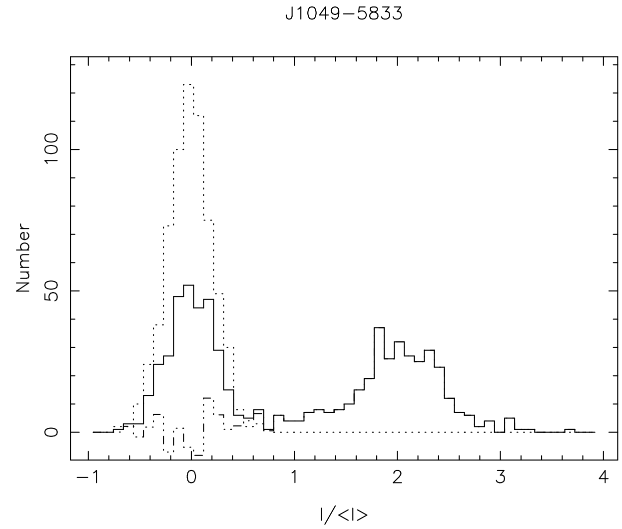

Figure 1. Histogram of on-pulse (solid line) and off-pulse (dotted line) intensities normalised by the mean pulse intensity for PSR J1049−5833. The dot-dashed line is the on-pulse histogram after subtraction of the null pulses (see text).

2 OBSERVATIONS AND RESULTS

Observations were made in two sessions, 2004 March 20 – 21 and 2004 June 8 – 9, using the H-OH receiver on the Parkes 64-m radio telescope. A filterbank system having a total bandwidth of 576 MHz centred at 1518 MHz with 192 3-MHz channels on each of two orthogonal linear polarisations was used. Signals from the two polarisations were detected, summed, high-pass filtered, one-bit digitised at 250 μs intervals and then written to digital linear tapes. The system equivalent flux density on cold sky was approximately 45 Jy.

Selection of the pulsar sample was based on data obtained in the Parkes Multibeam Pulsar Survey. Phase-time diagrams (see Manchester et al. 2001) for all pulsars detected in this survey were examined and those showing evidence for nulling were selected. Since the time resolution of the phase-time diagrams was typically 16 seconds, pulsars with nulls only of shorter or comparable duration were not selected. Sensitivity limitations also meant that nulls could only be detected among the stronger multibeam pulsars. Table 1 lists the selected pulsars along with their basic properties in the first seven columns: J2000 name, B1950 name (if it exists), pulse period P, period first time-derivative $\dot{P}$, characteristic age $\tau_c = P/(2\dot{P})$, dispersion measure (DM) and mean flux density at 1400 MHz. For most of the pulsars listed in Table 1, a continuous 2-hour observation was obtained.

In off-line processing the data were dedispersed and then folded at the topocentric pulsar period to form a series of sub-integrations. Sub-integration lengths are given in column (8) of Table 1; these ranged from 10 s to 60 s depending on the pulsar strength. This analysis is of course insensitive to nulls of duration less than or comparable to the sub-integration length. For two cases, PSR J1326−6700 and PSR J1401−6357, the signal/noise ratio was sufficiently good that sub-integration averaging was not required and intensities were computed for individual pulses. All of these pulsars have large DMs; consequently characteristic bandwidths for interstellar diffractive scintillation are much less than our observed bandwidth and scintillation fluctuations do not significantly affect the computed pulse intensities. For example, at a DM of 100 cm^{-3} pc (roughly the smallest in the sample), the typical bandwidth for diffractive scintillation at 1400 MHz is around 50 kHz, much less than our observed bandwidth.

Pulse energies for each sub-integration were determined by integrating under the pulse after subtraction of an off-pulse baseline and off-pulse energies were computed from a window of the same duration in the baseline region. Null fractions (NF), listed in column (9) of Table 1, were determined as follows. Histograms of the on-pulse and off-pulse intensities were formed (Fig. 1) both of which sum to the total number of sub-integrations N. A scaled version of the off-pulse histogram was subtracted from the on-pulse histogram so that the sum of the difference counts in bins with $I < 0$ was zero. The NF is then simply the scale factor with an uncertainty $\sqrt{n_p}/N$, where n_p is the number of null sub-integrations. Null lengths were measured as the time between the first pulse energy below a threshold (typically five times the rms fluctuation in the off-pulse energies) to the next above the threshold; column (10) lists the mean and rms values of these lengths for each observation. The final column lists the mean and rms null cycle times, that is, the mean and rms times from the onset of one null to the onset of the next.

In most cases, the rms scatter of the null length and null cycle time are comparable to the mean value, indicating a relatively "white" fluctuation spectrum. This was verified by directly computing power spectra for the sequence of pulse energies using a Fast Fourier Transform routine. However, in a few cases, e.g., PSR J1920+1040, quasi-periodic fluctuations are seen and the rms scatter of the cycle time is significantly less than the mean value. Because of the need to integrate for 10 s or more to give sufficient signal to noise for these relatively weak pulsars, this analysis was insensitive to periodic fluctuations related to subpulse drifting (e.g., Weltevrede et al. 2006).

Fig. 2 shows the observed pulse energy fluctuations as

Table 1. Observed pulsars and nulling parameters

(1) J2000 Name	(2) B1950 Name	(3) P (s)	(4) $\dot{P}$ (10^{-15})	(5) Age $(10^6$ yr)	(6) DM (cm^{-3} pc)	(7) S_{1400} (mJy)	(8) Int. (s)	(9) NF (%)	(10) Null len. (s)	(11) Null cycle (s)
J0846−3533	B0844−35	1.116	1.60	11.0	94	2.7	10	0	...	...
J1032−5911	B1030−58	0.464	3.00	2.4	418	0.93	20	0	...	...
J1049−5833	...	2.202	4.41	7.9	447	0.72	10	47(3)	84(86)	179(127)
J1326−6700	B1322−66	0.543	5.31	1.6	210	11.0	0	9.1(3)	1(1)	14(32)
J1401−6357	B1358−63	0.842	16.70	0.8	98	6.2	0	1.6(1)	2(3)	120(95)
J1412−6145	...	0.315	98.70	0.1	515	0.47	20	0	...	...
J1502−5653	...	0.535	1.83	4.6	194	0.39	10	93(4)	450(335)	515(360)
J1525−5417	...	1.011	16.20	1.0	235	0.18	20	16(5)	28(25)	138(102)
J1648−4458	...	0.629	1.85	5.4	925	0.55	60	1.4(11)	...	...
J1658−4306	...	1.166	42.80	0.4	845	0.80	60	0	...	...
J1701−3726	B1658−37	2.454	11.10	3.5	303	2.9	10	14(2)	16(9)	118(91)
J1702−4428	...	2.123	3.30	10.2	395	0.38	30	26(3)	42(24)	149(83)
J1703−4851	...	1.396	5.08	4.3	150	1.10	10	1.1(4)	...	...
J1717−4054	B1713−40	0.887	...	...	307	54	10	> 95	> 7000	> 7000
J1722−3632	B1718−36	0.399	4.46	1.4	416	1.60	20	0	...	...
J1727−2739	...	1.293	1.10	18.6	147	1.60	10	52(3)	48(37)	91(58)
J1812−1718	B1809−173	1.205	19.10	1.0	254	1.00	20	5.8(4)	23(6)	359(303)
J1820−0509	...	0.337	0.93	5.7	104	*	10	67(3)	71(69)	104(68)
J1831−1223	...	2.857	5.47	8.3	342	1.2	20	4(1)	23(7)	448(348)
J1833−1055	...	0.633	0.53	19.1	543	0.5	30	7(2)	...	...
J1843−0211	...	2.027	14.40	2.2	442	0.93	30	6(2)	46(23)	826(872)
J1916+1023	...	1.618	0.68	37.7	330	0.36	60	47(4)	70(43)	152(53)
J1920+1040	...	2.215	6.48	5.4	304	0.57	10	50(4)	43(25)	85(35)

a phase-time greyscale plot for six pulsars which appear to exhibit simple nulls, that is, a cessation of pulse emission with no associated mode changing. Observed NFs cover a wide range, with some pulsars, e.g., PSR J1525−5417, on most of the time, to nearly 100% for PSR J1717−4054. In this latter case, only one short burst was observed in the whole 2 hours, so the true null fraction is quite uncertain. Observed null durations and null cycle times also vary widely with some pulsars, e.g., PSR J1727−2739, having frequent short nulls and others having long timescales.

Fig. 3 collects together a group of five pulsars which show clear mode changes. In each case there are two identifiable modes. Mode A is defined to be the more common mode whereas mode B is less frequently observed. In four of these pulsars, the mean flux density is less in mode B, but for PSR J1703−4851 mode B is much stronger than mode A and dominates the long-term mean profile even though it is present for only about 15% of the time. For PSR J1701−3726 and PSR J1843−0211 the different modes are separated by null periods, but this is not so for the other three pulsars.

In the remainder of this Section we briefly discuss each pulsar in turn.

PSR J0846−3533 (B0844−35)

The phase-time plot shown in Fig. 3 shows that this apparently 3-component pulsar has brief intervals where it changes to a second mode (B) characterised by weaker emission in the leading and trailing components and stronger emission in the central component. These intervals, typically just 5 - 10 pulses long, are usually preceded by a few very weak (but not null) pulses. In fact no real nulls were observed in the 2-hour observation. As observed in other pulsars (Backer 1973; Rankin 1986), the intensity of the central component fluctuates to a much greater extent giving it a fluctuation spectrum which is "redder" than that for the other two components.

PSR J1032−5911 (B1030−58)

This pulsar has a simple, single-component profile of 50% width 7.7 ms (Hobbs et al. 2004) or just 0.017 of the period. Pulse energies are very highly modulated with strong bursts of emission 1 – 3 min in duration separated by similarly short intervals of weaker emission. There is no convincing evidence for real nulls in this pulsar.

PSR J1049−5833

This long-period pulsar, discovered in the Parkes multibeam survey (Manchester et al. 2001), also has a simple, single-component profile. The phase-time diagram given in Fig. 2 shows it to have frequent nulls with a typical duration of about 2 min. The active intervals are of similar duration giving it a NF of close to 50% (Table 1). The modulation spectrum has excess power at periods between 250 s and 750 s, somewhat longer than the mean cycle time of 179 s (Table 1). This difference can be attributed to the presence of numerous short nulls which interrupt longer bursts of emission (Fig. 2). These will reduce the computed mean cycle time, but will just add white noise to the power spectrum.

PSR J1326−6700 (B1322−66)

This pulsar has a mean pulse profile consisting of a basically triple profile with a weaker component on the leading edge of the profile. As shown in Fig. 4, it displays an intriguing combination of nulling and mode changing. Since it is

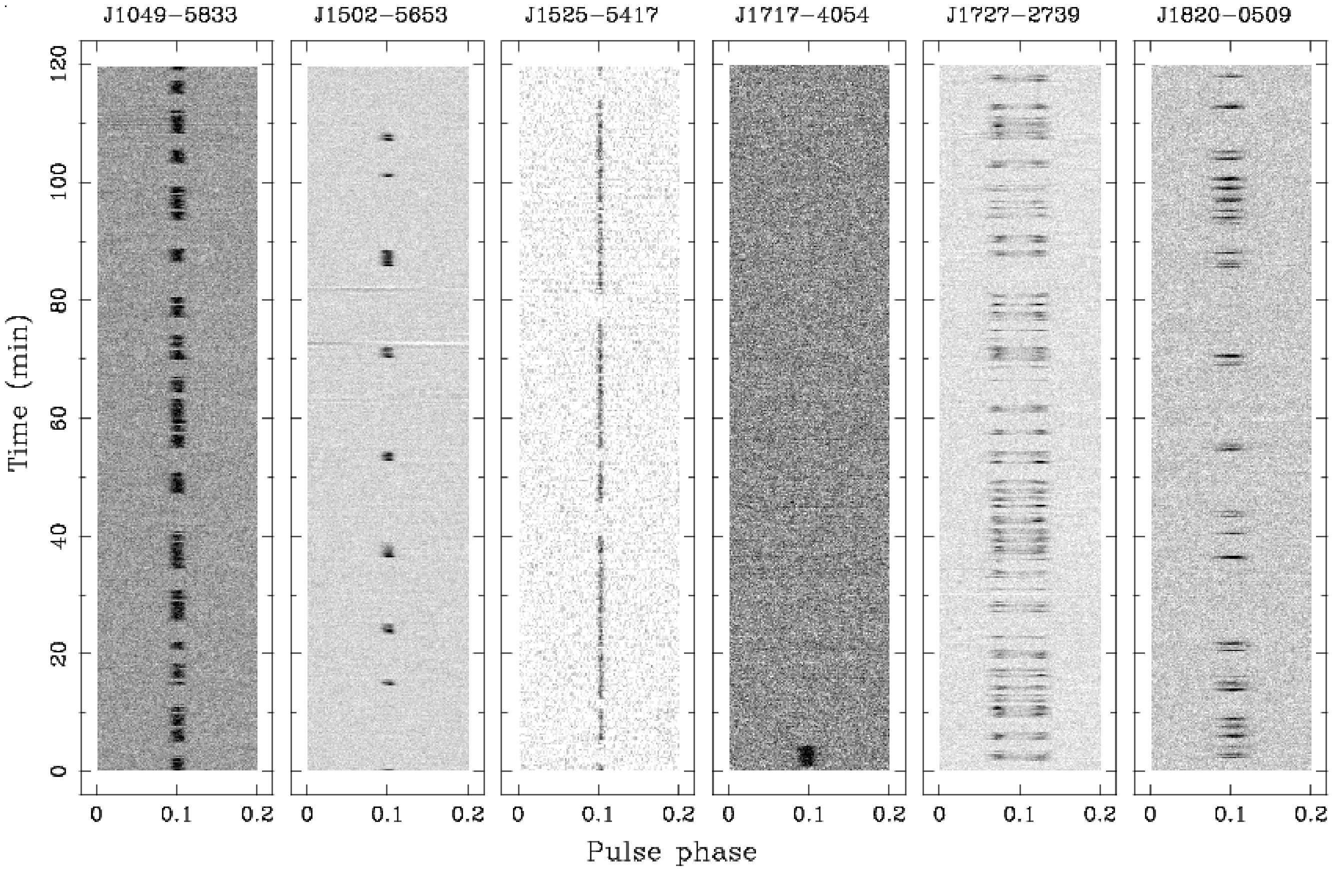

Figure 2. Phase-time plots for six pulsars which appear to show simple nulling. One fifth of the pulse period is shown in each case and the greyscale is linear in intensity from zero (white) to the maximum observed value (black).

relatively strong, averaging of data into subintegrations was not required and Fig. 4 shows individual pulse intensities. At intervals of 2 – 10 min (200 – 1000 pulses) emission from the two main components ceases, typically for less than a minute. (Table 1). During these "component" nulls, sporadic emission appears at the leading edge of the profile, forming the fourth leading component of the profile. The pulse phase of this mode-B emission is somewhat variable (see, for example, around pulse 3700 – 3750 in the lower inset of Fig. 4) and there are frequent short intervals during this mode-B emission when this leading component is undetectable. The mode A emission is more consistent with most pulses being visible although the relative (and absolute) amplitudes of the components vary greatly. Fig. 5 shows the very different mean pulse profiles for the two modes. There is some evidence for occasional drifting subpulses in this pulsar, for example, around pulses 3350 and 3560 in the lower inset. The drift is toward the trailing edge with a rate of approximately 0.008 cycles/period.

PSR J1401−6357 (B1358−63)

This pulsar has a narrow profile (50% width of 10 ms or 0.012 in phase) with a weak leading component (Hobbs et al. 2004). Individual pulse observations shown in Fig. 6 show it to have infrequent short nulls with an observed NF of just 1.6% (Table 1). Generally the active periods are relatively long (10 – 30 min), but as the upper inset in Fig. 6 shows, there can also be very short bursts of emission within a null interval. Fig. 6 also shows that the leading component is weak in the average profile because it is highly sporadic, with just occasional pulses which are comparable in flux density to those at the main peak.

PSR J1412−6145 This relatively weak pulsar showed no evidence for nulls in a 2-hr observation.

PSR J1502−5653

This pulsar has a NF of 93% (Table 1), among the highest known. The phase-time diagram given in Fig. 2 shows that active intervals last typically just a minute or so and are separated by 10 – 15 min. Consistent with these results, the fluctuation power spectrum shows a broad peak at periods between 400 and 1000 s. Although difficult to see in Fig. 2, closer examination of the data show that there are often short nulls of duration 5 – 10 periods within the bursts.

PSR J1525−5417

This weak pulsar has a very narrow pulse of 50% width 15 ms or 0.015 in phase (Kramer et al. 2003). Observations for this pulsar were affected by strong out-of-band interference, causing fluctuations in the baseline level, but the phase-time diagram (Fig. 2) shows it to have nulls of typical duration 3 – 4 min. With a NF of about 16% (Table 1), the active intervals are typically $\sim$ 20 min long but Fig. 2 shows that some bursts are much shorter. The fluctuation power spectrum has a broad peak at about 2400 s.

PSR J1648−4458

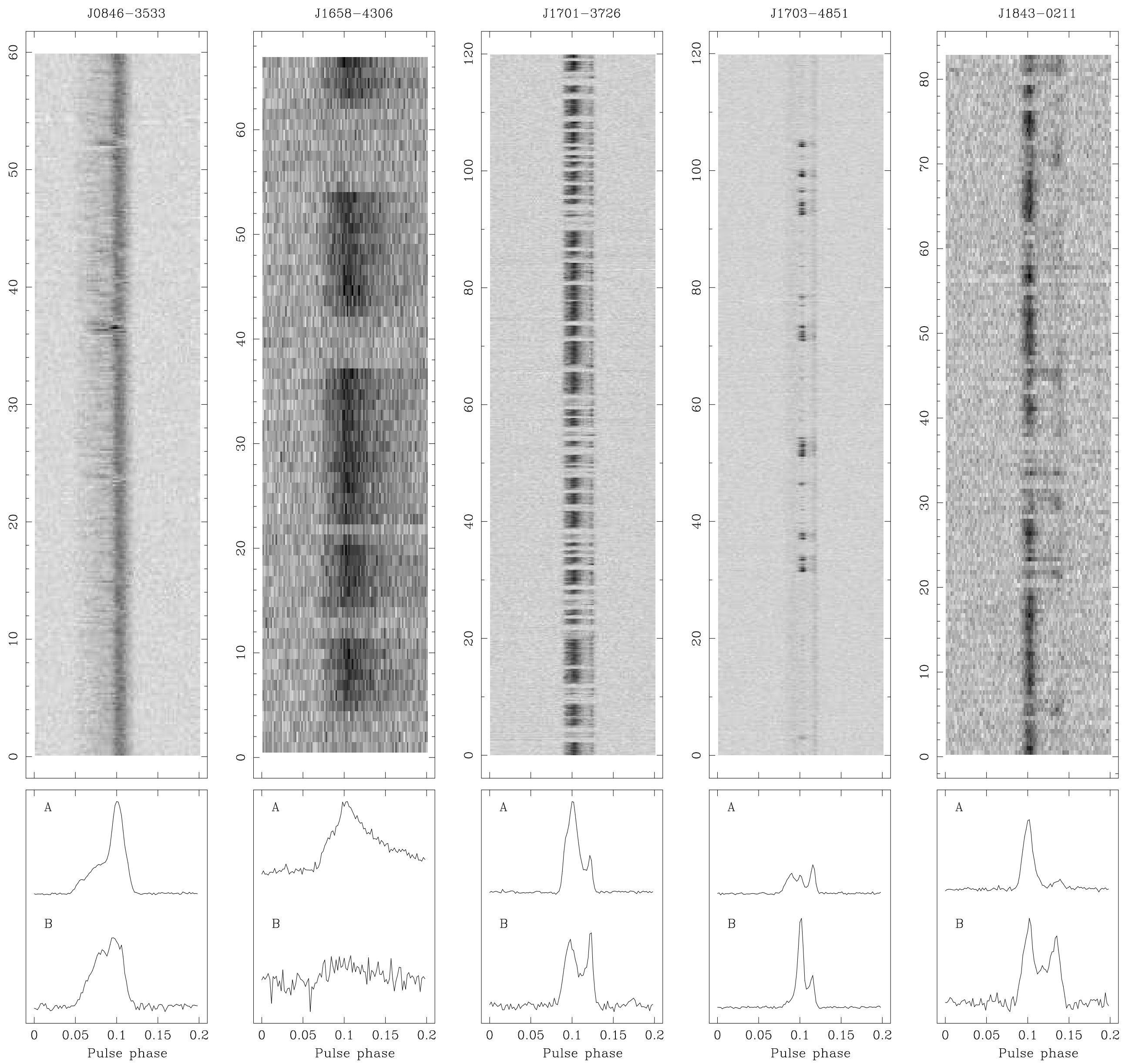

Figure 3. Phase-time plots for five pulsars which show mode changing. The greyscale is linear in intensity from zero to the maximum observed value. In the lower part of the figure, mean pulse profiles for the two observed modes are shown.

Another relatively weak pulsar from the Parkes multibeam survey (Kramer et al. 2003), this pulsar has sporadic bursts of emission with burst durations ranging between a few minutes and 15 min and a mean duty cycle of about 50%. However, weaker emission is clearly visible between the bursts, so there are no true nulls. Although there are no obvious differences in the mean pulse profiles for the burst and weak intervals, this may a form of mode changing.

PSR J1658−4306

This pulsar has a high DM and the pulse profile is significantly affected by interstellar scattering (Kramer et al. 2003). It is quite weak and 60 s integrations were necessary to give adequate signal-to-noise ratio. Fig. 3 appears to show five null periods of average duration 3 – 4 min in the 70-min data span. However, closer examination of the figure shows that, like PSR J1648−4458, there is weak but significant emission in the "null" intervals. This is verified by the pulse energy histogram which is bimodal but shows no null pulses. The apparent nulling is therefore better described as mode changing. Because of the low signal/noise ratio of the mode B profile, it is difficult to tell if the profiles for the two modes are different. The intrinsic (unscattered) mode A profile is probably double and there is some indication that the stronger trailing component is absent or weaker in the mode B profile.

PSR J1701−3726 (B1658−37)

As Fig. 3 shows, this pulsar has frequent short nulls giving a broad peak in the fluctuation spectrum for periods between 60 and 500 s. Most of the time, the pulsar has a three-component profile with the middle (but not central)

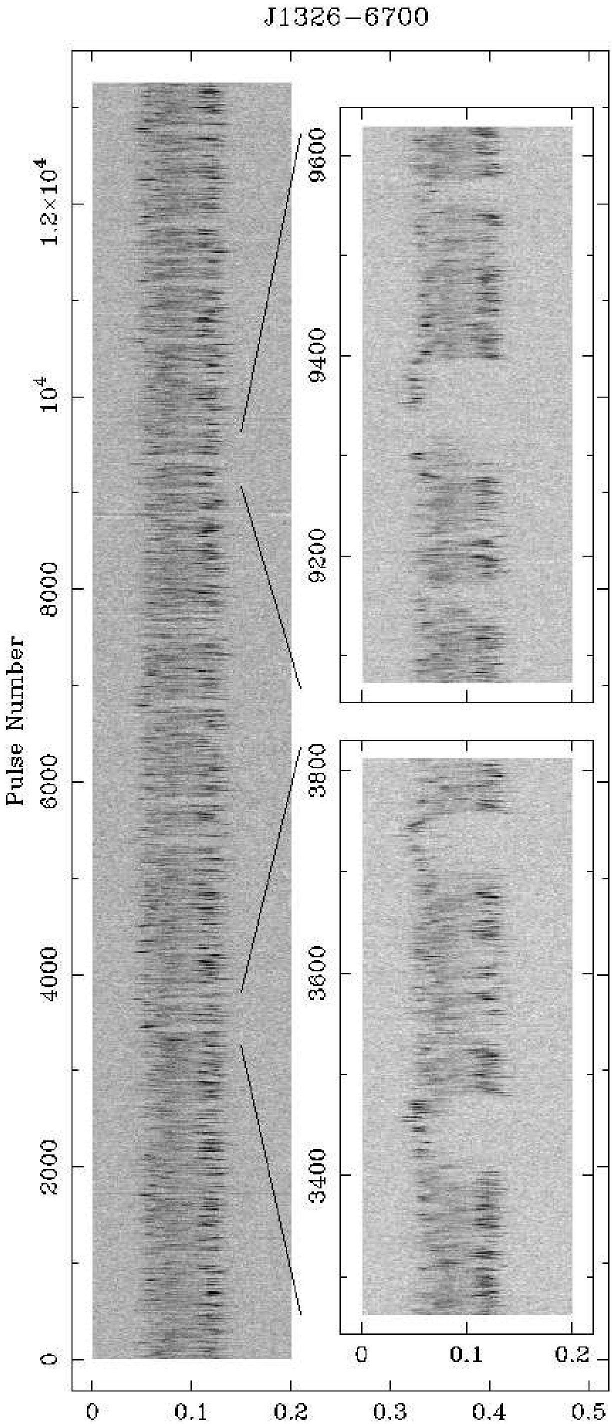

Figure 4. Phase-time diagram showing intensity variations for individual pulses from PSR J1326−6700. The insets show two portions of the data with an expanded scale.

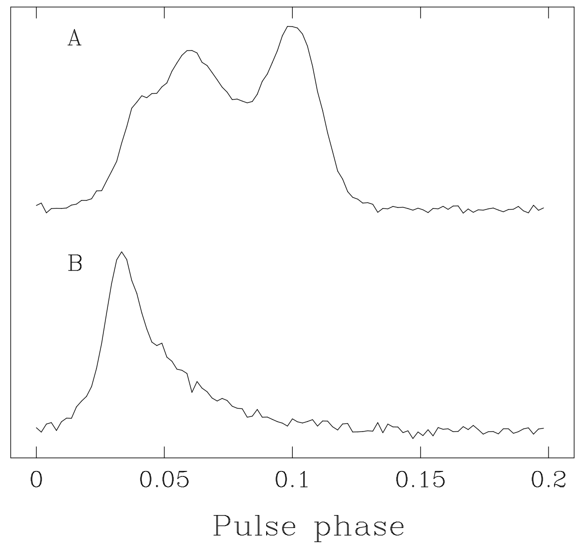

Figure 5. Mean pulse profiles for the two modes of emission from PSR J1326−6700.

component the strongest. However, as illustrated in Fig. 3, on occasions this middle component becomes much weaker and the pulse profile is basically double. Within a given burst, the pulsar remains in one mode, i.e., the two modes are always separated by a null interval. Mode B emission is both rarer and weaker than mode A, with only seven or eight short bursts, each of a minute or two in duration, during the 2-hr observation.

PSR J1702−4428

Another long-period and rather weak pulsar which fluctuates greatly in strength; it appears to be in a null state about one quarter of the time. The fluctuation spectrum has excess power in the range 85 s to 1500 s.

PSR J1703−4851

As shown in Fig. 3, this pulsar exhibits a fascinating form of mode changing in which the central and trailing components of the triple profile are intermittently enhanced relative to the leading component. We define the most common, although in this case weaker, mode to be mode A. Mode A emission appears to be quite steady, at least with the 10-s integrations used in Fig. 3. The enhanced emission of mode B occurs in short bursts of duration from just a few seconds up to 1 or 2 min and is present for about 15% of the time. For at least the central component, the longer bursts of mode B emission are interrupted by short intervals of weaker or maybe no emission.

PSR J1717−4054 (B1713−40)

This pulsar had only one intense burst of duration about 3.5 min during the whole 2-hr observation (Fig. 2), giving it a null fraction of at least 95%, the highest value measured so far. Although discovered in the Johnston et al. (1992) Galactic Plane survey, this pulsar still has no measured $\dot{P}$ and hence characteristic age. This is certainly because the high NF makes it difficult to observe. We note that the lack of a measured $\dot{P}$ for this strongly nulling pulsar is likely to bias statistics on the dependence of nulling on $\dot{P}$-related parameters.

PSR J1722−3631 (B1718−36)

Pulse emission from this pulsar is highly modulated but no nulls were observed in a 2-hr observation.

PSR J1727−2739

This pulsar has a classic double mean pulse profile of 50% width 90 ms or 0.07 of the pulse period. The phase-time diagram given in Fig. 2 shows that the pulsar emits frequent short bursts separated by null intervals. There is no evidence

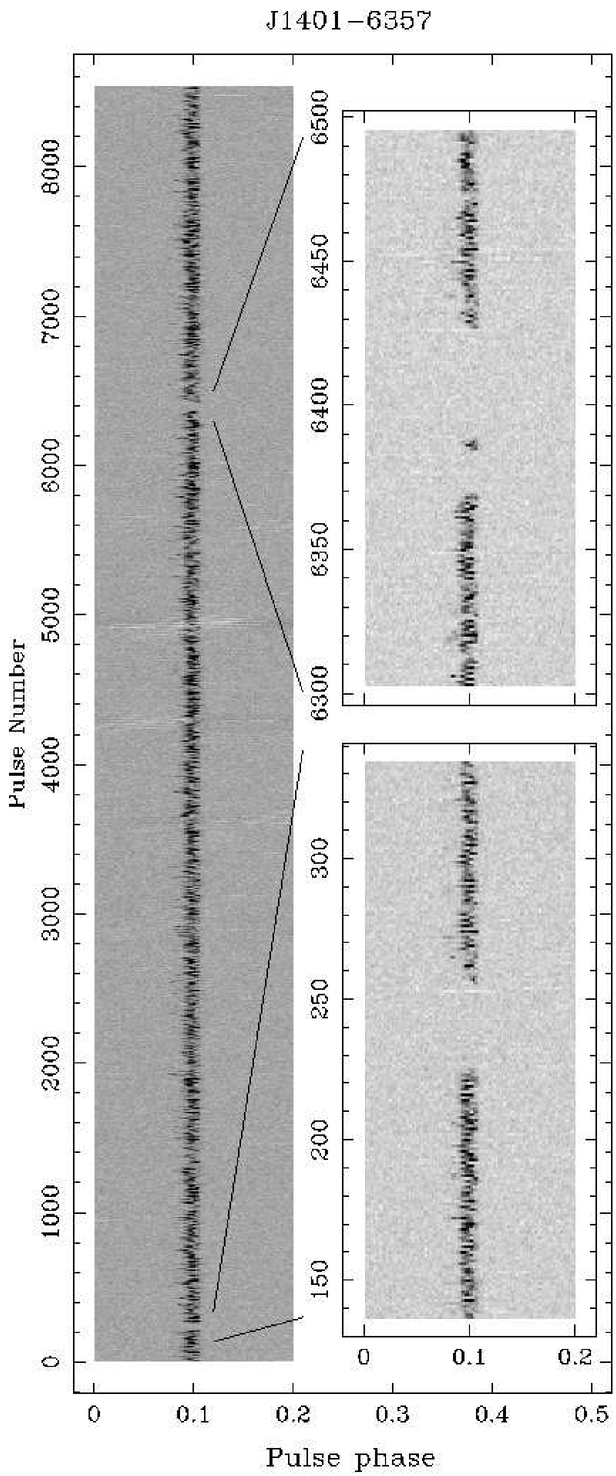

Figure 6. Phase-time diagram showing intensity variations for individual pulses from PSR J1401−6357. The insets show two portions of the data with an expanded scale.

for any mode changing. Typical burst lengths are about a minute and null lengths a little longer, although both are quite variable, giving a rather flat modulation spectrum. The observed NF is about 50% (Table 1).

PSR J1812−1718 (B1809−173)

The mean pulse profile for this pulsar is dominated by a narrow leading component of 50% width 19 ms or 0.015 periods (Hobbs et al. 2004). There is a weak trailing component of similar width which overlaps with the main component. The phase-time diagram shows frequent short nulls of average duration about 25 s with an observed NF of about 6%. There are no significant periodicities in the modulation spectrum (with sampling interval 20 s).

PSR J1820−0509

This pulsar, discovered in the second "reprocessing" phase of the Parkes multibeam survey (Lorimer et al. 2006), has a relatively short period but is old with a characteristic age of 5.7 Myr (Table 1). As Fig. 2 shows, it is in a null state most of the time with only short active periods. The derived NF (Table 1) is 67% and the mean on-time is less than a minute. The fluctuation power spectrum shows no significant periodicities and there is no evidence for mode changing.

PSR J1831−1223

This long-period pulsar has a double-peaked mean profile of 50% width 98 ms or 0.034 in pulse phase (Morris et al. 2002). It suffers frequent short nulls of mean duration about 25 s (Table 1) but the NF is low. The phase-time plot suggests possible mode changing, but unfortunately the signal-to-noise ratio is rather poor and a more definitive statement cannot be made based on these data. The fluctuation power spectrum has excess power at periods between 50 and 200 s.

PSR J1833−1055

This weak pulsar required an integration time of 30 s to give adequate signal-to-noise ratio in the phase-time plot. The pulsar is very bursty with intervals of strong emission typically lasting a minute or two. Weaker emission is seen between these bursts but there appear to be a few per cent of null pulses. There is a peak in the fluctuation power spectrum at about 400 s period with excess power between 200 and 900 s.

PSR J1843−0211

This long-period pulsar has a moderately large period derivative, giving it a characteristic age of 2.2 Myr (Table 1). The mean pulse profile has a strong leading component and much weaker trailing component, but is never-the-less clearly double-peaked. Although weak (30 s integrations were required) the pulsar appears to have occasional short nulls, of typical duration less than or about one minute (Fig. 3). There is clear evidence of mode changing with the leading component much stronger in the dominant mode (A) and the two components weaker and of approximately equal amplitude in the secondary mode (B). Although mode B is present for only a few per cent of the time, it is the dominant contributor to the trailing component of the mean profile.

PSR J1916+1023

This pulsar has a two- or possibly three-component profile (Hobbs et al. 2004). It has a large characteristic age and is very weak, requiring 60-s integrations for sufficient signal-to-noise ratio. It appears to be in a null state for about 50% of the time with many short bursts of emission, typically just one or two minutes in duration. There is no significant evidence for mode changing.

PSR J1920+1040

This pulsar has single-component mean pulse profile

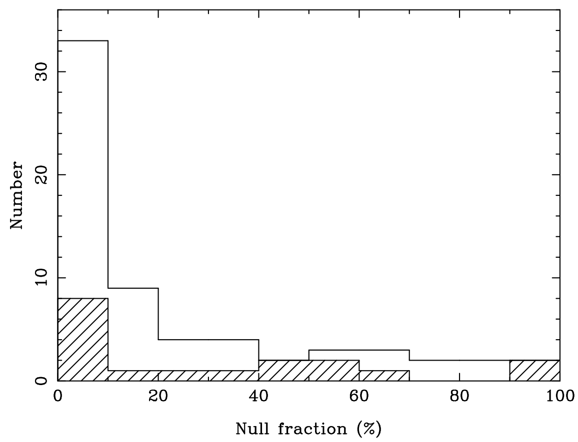

Figure 7. Histogram of observed null fractions. Values from the present observations are shown hatched.

of 50% width 45 ms or 0.020 of the period (Hobbs et al. 2004). It has frequent quasi-periodic bursts of typical duration about 40 s separated by somewhat longer nulls, giving it a null fraction of about 50% (Table 1). There is no evidence for mode changing. The fluctuation power spectrum has a strong peak at about 90 s periodicity with excess power between 60 and 340 s.

3 DISCUSSION

Most of the pulsars in this study were discovered in the Parkes multibeam pulsar survey. The observation time per pointing in this survey, 35 min, was much longer than for other large-scale surveys. This long integration time facilitated the discovery of longer-period pulsars (e.g. McLaughlin et al. 2003) which are more likely to null (Biggs 1992). Furthermore, it aided the identification of nulling pulsars whose off times are more than a few minutes, sources that would often be missed by surveys with observation times of this order. The extreme example of this is the discovery of "rotating radio transients" or RRATs (McLaughlin et al. 2006), pulsars in which just single pulses are observed at intervals of minutes to hours.

As can be seen from Table 1, seven of the 23 pulsars in our sample have NFs of 50% or more (within the uncertainties), with two having NFs of order 95%, the largest known (apart from the RRATs). Table 2 lists previously known nulling pulsars and their NF. While some of these values may be misleading because of low signal-to-noise ratio in the observations, the table gives the best available indication of the distribution of nulling in known pulsars. Fig. 7 shows that the present work has substantially increased the number of pulsars with high NF, doubling the number known with NF $\geq$ 50%. Although our observations are generally not very sensitive to short nulls (because of limited signal/noise on these relatively weak pulsars), it is clear that pulsars with low NF are much more common than those with high NF.

Fig. 8 shows the distribution of known nulling pulsars on the P–$\dot{P}$ diagram.[1] This diagram suggests that the degree of nulling is related more to age than period. Although some

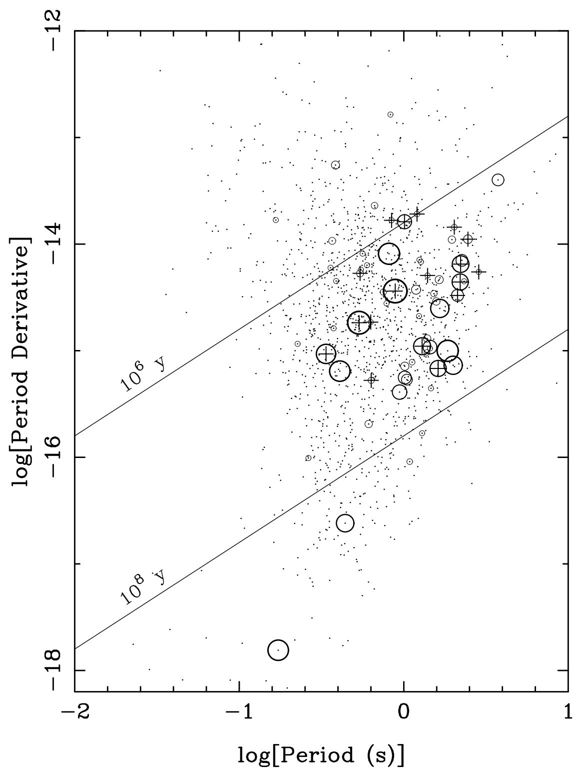

Figure 8. Plot of pulsar period versus period derivative for Galactic disk radio pulsars. Nulling pulsars are marked by a circle whose area is proportional to the null fraction with a lower bound of 5%. Pulsars discussed in this paper are marked by a cross. Lines of constant characteristic age are shown.

pulsars with large τ_c have small NF, all of the pulsars with large NF have $\tau_c > 1$ Myr and most have $\tau_c > 5$ Myr. In contrast, even excluding the recycled pulsar J1744−3922 with a period of 0.172 s, PSR J1820−0509, with period of 0.337 s and age of 5.7 Myr has a NF of 67%, whereas PSR B0525+21, with a period of 3.75 s and an age of 1.5 Myr has a NF of 25%. The longest-period pulsar in our sample, PSR J1831−1223 (2.86 s), has a NF of just 4%.

There is no strong correlation of NF with profile morphology. As Figs 2 – 6 shows, nulls are observed in pulsars with both narrow single-component pulse profiles and wider multi-component profiles. As a fraction of the population, nulling tends to be more common in multi-component profiles (Rankin 1986; Biggs 1992); such pulsars tend to have larger τ_c so this is just the same correlation as that shown in Fig. 8. Unfortunately, polarisation data exist for only a few of these pulsars, so no clear relationships with impact parameter or other polarisation characteristics can be drawn. There is no obvious correlation of null cycle time with pulse period or characteristic age.

Do RRATs represent an extreme form of pulse nulling or are they an intrinsically different phenomenon? Based on a study of the pulse modulation in PSR B0656+14, Weltevrede et al. (2006) have suggested that RRATs are highly modulated pulsars which occasionally emit very in-

[1] Data from the ATNF Pulsar Catalogue (http://www.atnf.csiro.au/research/pulsar/psrcat; Manchester et al. 2005)

Table 2. Previously known nulling pulsars

J2000 Name	B1950 Name	P (s)	$\dot{P}$ (10^{-15})	Age $(10^6$ yr)	NF (%)	Reference
J0034−0721	B0031−07	0.943	0.41	36.6	0.1	htt70
J0151−0635	B0148−06	1.465	0.44	52.4	2.5	big92
J0304+1932	B0301+19	1.388	1.30	17.0	5	ran86
J0452−1759	B0450−18	0.549	5.75	1.5	0.45	big92
J0528+2200	B0525+21	3.746	40.00	1.5	5	rit76
J0630−2834	B0628−28	1.244	7.12	2.8	0.15	big92
J0659+1414	B0656+14	0.385	55.00	0.1	4	big92
J0738−4042	B0736−40	0.375	1.62	3.7	0.2	big92
J0742−2822	B0740−28	0.167	16.80	0.2	0.1	big92
J0754+3231	B0751+32	1.442	1.08	21.2	0.5	wab+86
J0814+7429	B0809+74	1.292	0.17	122.0	0.02	la83
J0820−1350	B0818−13	1.238	2.11	9.3	0.01	la83
J0828−3417	B0826−34	1.849	1.00	29.4	5	dll+79
J0837+0610	B0834+06	1.274	6.80	3.0	0.6	big92
J0837−4135	B0835−41	0.752	3.54	3.4	1.0	rit76
J0942−5552	B0940−55	0.664	22.90	0.5	3	wab+86
J0943+1631	B0940+16	1.087	0.09	189.0	6	big92
J1115+5030	B1112+50	1.656	2.49	10.5	5	rit76
J1136+1551	B1133+16	1.188	3.73	5.0	2.5	rit76
J1239+2453	B1237+25	1.382	0.96	22.8	2.5	rit76
J1243−6423	B1240−64	0.388	4.50	1.4	2	big92
J1430−6623	B1426−66	0.785	2.77	4.5	0.025	big92
J1456−6843	B1451−68	0.263	0.10	42.5	1.7	big92
J1532+2745	B1530+27	1.125	0.78	22.9	2	wab+86
J1649+2533	...	1.015	0.56	28.8	5	lwf+04
J1731−4744	B1727−47	0.830	164.00	0.1	0.05	big92
J1744−3922	...	0.172	0.00	1760.0	9	big92
J1745−3040	B1742−30	0.367	10.70	0.5	0.7	big92
J1752−2806	B1749−28	0.563	8.13	1.1	75	fsk+04
J1752+2359	...	0.409	0.64	10.1	5	lwf+04
J1820−0427	B1818−04	0.598	6.33	1.5	0.13	big92
J1900−2600	B1857−26	0.612	0.21	47.4	2.5	rit76
J1910+0358	B1907+03	2.330	4.47	8.3	2	big92
J1932+1059	B1929+10	0.227	1.16	3.1	0.5	big92
J1933+2421	B1931+24	0.814	8.11	1.6	80	klo+06
J1935+1616	B1933+16	0.359	6.00	0.9	0.03	big92
J1944+1755	B1942+17	1.997	0.73	43.3	1	wab+86
J1945−0040	B1942−00	1.046	0.54	31.0	60	lcx02
J1946+1805	B1944+17	0.441	0.02	290.0	5	rit76
J2048−1616	B2045−16	1.962	11.00	2.8	2.5	rit76
J2113+4644	B2111+46	1.015	0.71	22.5	2.5	rit76
J2157+4017	B2154+40	1.525	3.43	7.0	2.5	rit76
J2305+3100	B2303+30	1.576	2.89	8.6	1.7	rwr05
J2317+2149	B2315+21	1.445	1.05	21.9	0.5	wab+86
J2321+6024	B2319+60	2.256	7.04	5.1	5	rit76
J2330−2005	B2327−20	1.644	4.63	5.6	1	big92

Note: where Biggs (1992) states that nulls have been observed, but only quotes an upper limit for the NF, the table value has been taken as half the quoted upper limit.
References: big92: Biggs (1992), dll+79: Durdin et al. (1979), fsk+04: Faulkner et al. (2004), htt70: Huguenin et al. (1970), klo+06: Kramer et al. (2006), la83: Lyne & Ashworth (1983), lcx02: Lorimer et al. (2002), lwf+04: Lewandowski et al. (2004), ran86: Rankin (1986), rit76: Ritchings (1976), rwr05: Redman et al. (2005), wab+86: Weisberg et al. (1986).

tense pulses but which are too distant for the "normal" emission to be detectable (cf. Johnston & Romani 2002). Note that these are not "giant" pulses as observed in the Crab pulsar (e.g., Hankins et al. 2003), other young pulsars (Johnston & Romani 2003) and some millisecond pulsars (e.g., Knight et al. 2006), but simply very intense "normal" pulses. If this is the correct explanation, then RRATs are not directly related to nulling pulsars.

On the other hand, nulling and mode changing appear to be intimately related. For example, in PSR J1701−3726 (Fig. 3), the two modes are always separated by a null interval. van Leeuwen et al. (2002) find that PSR B0809+74 emits in a different mode after nulls and Redman et al. (2005) find that different modes in PSR B2303+30 have different nulling properties. PSR J1703−4851 (Fig. 3) appears to be similar with few or no nulls in the weaker but more common mode. As mentioned in § 1, weak emission with a different pulse profile has been found in the "null" intervals of PSR B0826−34 (Esamdin et al. 2005). Very similar situations exist in PSR J1326−6700 (Fig. 4) where emission from the normal (mode A) profile ceases and is replaced by emission from a new leading component, and PSRs J1648−4458 and J1658−4306, where weak emission is observed in what at first glance appear to be nulls. Simultaneous multi-frequency observations (e.g., Bartel et al. 1982) show that both nulling and mode changing are broad-band phenomena. Finally, there is the fascinating observation by Kramer et al. (2006) of the change in slow-down rate of PSR B1931+24 when the pulsar is in a null state.

All of these observations suggest that both nulling and mode changing result from large-scale and persistent changes in the magnetospheric current distribution. Mode changes must be a manifestation of a redistribution of current flow in the magnetosphere, resulting in changes in the radio beam emission pattern and hence in the observed pulse profile. Nulls may result from a cessation of (or at least a large reduction in) the current as suggested by the observations of PSR B1931+24 (Kramer et al. 2006), but may also result from a current redistribution which leads to a beam pattern with little or no power in our direction. This latter interpretation is favoured by the increasing number of detections of weak emission, generally with a different pulse profile, in apparent null intervals. Both nulls and mode changes are typically sudden transitions, occurring within one pulse period, although exceptions apparently exist (Deich et al. 1986; Lewandowski et al. 2004).

The concept of "tipping points" is well known in the study of non-linear complex systems, for example, in climate science. This is a situation where a small perturbation can lead to a sudden change to a different quasi-stable state. The transitions are fundamentally related to positive feedback and can be reversible.[2] Evidently the pulsar pulse emission process in at least some pulsars is subject to such instabilities. For example, if a small perturbation in current flow results in a change in the accelerating potential or magnetic field configuration which enhances the change, an instability could develop. The observations imply changes in current flow which are quite drastic, completely changing the observed pulse profile and its polarisation and modulation characteristics, and in some cases making the pulsar unobservable. What causes these instablities, why they tend to be bistable and what determines their timescale are currently unanswered questions. It is clear that they are most common in old pulsars but there is a wide range in the observed properties of pulsars which are subject to mode changing and nulling.

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[2] For an interesting discussion of the concept, see http://www.realclimate.org/index.php/archives/2006/07/runaway-tipping-points-of-no-return/.

REFERENCES

Backer D. C., 1970a, Nature, 228, 1297

Backer D. C., 1970b, Nature, 228, 42

Backer D. C., 1973, ApJ, 182, 245

Bartel N., Morris D., Sieber W., Hankins T. H., 1982, ApJ, 258, 776

Biggs J. D., 1992, ApJ, 394, 574

Deich W. T. S., Cordes J. M., Hankins T. H., Rankin J. M., 1986, ApJ, 300, 540

Durdin J. M., Large M. I., Little A. G., Manchester R. N., Lyne A. G., Taylor J. H., 1979, MNRAS, 186, 39P

Esamdin A., Lyne A. G., Graham-Smith F., Kramer M., Manchester R. N., Wu X., 2005, MNRAS, 356, 59

Faulkner A. J., Stairs I. H., Kramer M., Lyne A. G., Hobbs G., Possenti A., Lorimer D. R., Manchester R. N., McLaughlin M. A., D'Amico N., Camilo F., Burgay M., 2004, MNRAS, 355, 147

Gil J. A., Jessner A., Kijak J., Kramer M., Malofeev V., Malov I., Seiradakis J. H., Sieber W., Wielebinski R., 1994, A&A, 282, 45

Hankins T. H., Kern J. S., Weatherall J. C., Eilek J. A., 2003, Nature, 422, 141

Hobbs G., Faulkner A., Stairs I. H., Camilo F., Manchester R. N., Lyne A. G., Kramer M., D'Amico N., Kaspi V. M., Possenti A., McLaughlin M. A., Lorimer D. R., Burgay M., Joshi B. C., Crawford F., 2004, MNRAS, 352, 1439

Huguenin G. R., Taylor J. H., Troland T. H., 1970, ApJ, 162, 727

Janssen G. H., van Leeuwen J., 2004, A&A, 425, 255

Johnston S., Lyne A. G., Manchester R. N., Kniffen D. A., D'Amico N., Lim J., Ashworth M., 1992, MNRAS, 255, 401

Johnston S., Romani R., 2002, MNRAS, 332, 109

Johnston S., Romani R., 2003, ApJ, 590, L95

Kaspi V. M., Stinebring D. R., 1992, ApJ, 392, 530

Knight H. S., Bailes M., Manchester R. N., Ord S. M., Jacoby B. A., 2006, ApJ, 640, 941

Kramer M., Bell J. F., Manchester R. N., Lyne A. G., Camilo F., Stairs I. H., D'Amico N., Kaspi V. M., Hobbs G., Morris D. J., Crawford F., Possenti A., Joshi B. C., McLaughlin M. A., Lorimer D. R., Faulkner A. J., 2003, MNRAS, 342, 1299

Kramer M., Lyne A. G., O'Brien J. T., Jordan C. A., Lorimer D. R., 2006, Science, 312, 549

Lewandowski W., Wolszczan A., Feiler G., Konacki M., Sołtysiński T., 2004, ApJ, 600, 905

Lorimer D. R., Camilo F., Xilouris K. M., 2002, ApJ, 123, 1750

Lorimer D. R., Faulkner A., Lyne A. G., Manchester R. N., Kramer M., McLaughlin M. A., Hobbs G., Possenti A., Stairs I. H., Camilo F., Burgay M., D'Amico N., Corongui A., Crawford F., 2006, MNRAS

Lyne A. G., Ashworth M., 1983, MNRAS, 204, 519

McLaughlin M. A., Stairs I. H., Kaspi V. M., Lorimer D. R., Kramer M., Lyne A. G., Manchester R. N., Camilo F., Hobbs G., Possenti A., D'Amico N., Faulkner A. J., 2003, ApJ, 591, L135

Manchester R. N., Hobbs G. B., Teoh A., Hobbs M., 2005, AJ, 129, 1993

Manchester R. N., Lyne A. G., Camilo F., Bell J. F., Kaspi V. M., D'Amico N., McKay N. P. F., Crawford F., Stairs

I. H., Possenti A., Morris D. J., Sheppard D. C., 2001, MNRAS, 328, 17

McLaughlin M. A., Lyne A. G., Lorimer D. R., Kramer M., Faulkner A. J., Manchester R. N., Cordes J. M., Camilo F., Possenti A., Stairs I. H., Hobbs G., D'Amico N., Burgay M., O'Brien J. T., 2006, Nature, 439, 817

Morris D. J., Hobbs G., Lyne A. G., Stairs I. H., Camilo F., Manchester R. N., Possenti A., Bell J. F., Kaspi V. M., Amico N. D., McKay N. P. F., Crawford F., Kramer M., 2002, MNRAS, 335, 275

Rankin J. M., 1986, ApJ, 301, 901

Redman S. L., Wright G. A. E., Rankin J. M., 2005, MNRAS, 357, 859

Rickett B. J., 1990, Ann. Rev. Astr. Ap., 28, 561

Ritchings R. T., 1976, MNRAS, 176, 249

Taylor J. H., Manchester R. N., Huguenin G. R., 1975, ApJ, 195, 513

van Leeuwen A. G. J., Kouwenhoven M. L. A., Ramachandran R., Rankin J. M., Stappers B. W., 2002, A&A, 387, 169

Weisberg J. M., Armstrong B. K., Backus P. R., Cordes J. M., Boriakoff V., Ferguson D. C., 1986, AJ, 92, 621

Weltevrede P., Edwards R. T., Stappers B. W., 2006, A&A, 445, 243

Weltevrede P., Stappers B. W., Rankin J. M., Wright G. A. E., 2006, ApJ, 645, L149